GUIDED WAVE ELECTROOPTIC AND ACOUSTOOPTIC TUNABLE FILTER APPARATUS AND METHOD

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The Applicant hereby claims the benefit of the earlier filing date of December 23, 1999, of Provisional Application Serial No. 60/173,018, under 35 U.S.C. §119(e).

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The U.S. Government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms, as provided for by the terms of Project No. 32192-72220 sponsored by the State of Texas and Project No. 32525-57570 sponsored by Lockheed Martin Corporation.

BACKGROUND OF THE INVENTION

This invention relates to an apparatus and method for the selection of light of one optical frequency or wavelength channel from a multiplicity of channels or optical frequencies being transmitted in an optical fiber or optical waveguide. The invention can also be used to efficiently combine light waves of different frequencies.

Filter technology for wavelength division multiplexing (WDM) is one of the most active research and development topics in the optical fiber telecommunications field. A number of guided wave filter approaches are at various stages of development, including the fiber Bragg grating, fiber Fabry-Perot, asymmetrical Mach Zehnder interferometer (MZI),

waveguide grating router (WGR), acoustooptic tunable filter (AOTF), and electrooptic tunable filter (EOTF).

Of these technologies, only the AOTF and EOTF can be tuned from one channel to another at near-microsecond (for the AOTF) or sub-microsecond (for the EOTF) speeds needed for fast packet-switched networks. As illustrated in Figs. 1 and 2, conventional, prior art, schemes for implementing the AOTF and EOTF have several features in common. Both are fabricated in ferroelectric insulating substrates such as lithium niobate, and make use of a four-port MZI structure formed from waveguides which are single mode for both horizontally polarized light (TE) and vertically polarized light (TM). Both filters make use of phase-matched polarization conversion in the arms of the MZI, and ideally their performance is independent of the incident polarization state. Another common feature of the conventional AOTF and EOTF designs is that they both use polarizing beam splitters (PBSs), optical circuit elements which have proven difficult to fabricate with the high polarization extinction ratios needed to meet filter requirements.

A prior art four-port beam splitter is illustrated in Fig. 3. Light incident in port 1 will, in general, be split between output port 1 (straight through port) and output port 2 (crossover port). The requirement for a PBS is that, for i,j = 1,2: $(f_{TE})_{ii} = 1$; $(f_{TE})_{ij} = 0,\ j \neq i$; $(f_{TM})_{ii} = 0$; $(f_{TM})_{ij} = 1,\ j \neq i$, where $(f_P)_{ij}$ is the fraction of the power in input port i which couples to output port j for polarization P. (It should be noted that an alternative PBS design is obtained by reversing "TE" and "TM" in these expressions). As more fully disclosed hereafter, Applicants' invention is directed to new AOTF and EOTF configurations which allow for an

additional degree of freedom in beam splitter characteristics and which are, therefore, much easier to fabricate than the conventional filters.

Principles of Operation of Conventional AOTFs and EOTFs

The prior art AOTF depicted in Fig. 1 makes use of the strain-optic effect from a traveling acoustic wave to produce polarization conversion in the two arms of the MZI structure, which is fabricated on a $LiNbO_3$ substrate. The conversion is very efficient at the optical frequency ν_j for which a phase matching condition is satisfied, such that the acoustic wavelength exactly matches the TE ↔ TM polarization beat length in the waveguide. At other optical frequencies for which the phase matching condition is not satisfied, little polarization conversion occurs. Horizontally polarized (TE) light incident on the filter at a frequency ν_i is directed by the first PBS into its straight through output port - the upper waveguide in the Mach-Zehnder. If the polarization is not converted in that waveguide ($i \neq j$), the light incident on the second PBS is also directed to its straight through output port, which is the upper output port of the filter. If the polarization is converted ($i = j$), the light incident on the second beam splitter emerges from its crossover port, which is the filter's lower output port.

On the other hand, vertically polarized (TM) light incident on the filter at a frequency ν_i is directed by the first PBS into its crossover output port, the lower waveguide in the MZI. If the polarization is not converted in that waveguide ($i \neq j$), the light incident on the second PBS is also directed to its crossover port, the filter's upper output port. If the polarization is converted ($i = j$), the light incident on the second beam splitter emerges from its straight through output port, which is the filter's lower output port. Thus, for either polarization, TE

or TM, the light at the selected frequency ν_j emerges from the lower output port of the filter, and all other frequencies exit via the upper output port. Tuning of the filter to change the selected optical frequency is accomplished by changing the acoustic frequency.

Conceptually, the conventional EOTF differs from the AOTF in two respects: both the polarization coupling mechanism and the tuning method are different. In the EOTF illustrated in Fig.2, tuning is accomplished by an applied voltage V_j which changes the waveguide birefringence and hence the optical frequency ν_j for which phase matching occurs. A spatially periodic strain-inducing film causes polarization coupling via the strain-optic effect. In other EOTF designs, a spatially periodic electric field produced by an interdigital electrode structure induces the polarization coupling via the electrooptic effect.

Beam Splitter Description

Performance of the four-port beam splitter of Fig. 3 is described by the expression

$$\mathbf{O}_P = \mathbf{C}_P \mathbf{I}_P, \tag{1}$$

with

$$\mathbf{I}_P = \begin{bmatrix} (\mathrm{I}_P)_1 \\ (\mathrm{I}_P)_2 \end{bmatrix}, \tag{2}$$

$$\mathbf{O_P} = \begin{bmatrix} (O_P)_1 \\ (O_P)_2 \end{bmatrix}, \tag{3}$$

and

$$\mathbf{C_P} = \begin{bmatrix} (c_P)_{11} & (c_P)_{12} \\ (c_P)_{12} & (c_P)_{11} \end{bmatrix} \tag{4}$$

In these expressions P represents the polarization (TE or TM), $(I_P)_i$ is the input electric field amplitude in port i (i = 1,2), $(O_P)_i$ is the corresponding output electric field amplitude, and the coupling coefficients are

$$(c_P)_{11} = \cos(\kappa_P L) \tag{5}$$

$$(c_P)_{12} = i \sin(\kappa_P L), \tag{6}$$

with κ_P the interwaveguide coupling coefficient and L the effective length of the coupling region. The analysis neglects loss and assumes that the coupled waveguides are identical and support a single mode for each polarization, but that in general the mode field patterns and hence the coupling coefficients are different for the two polarizations.

For a polarizing beam splitter with TE polarization directed in the straight through path and TM polarization crossing over, the coupling coefficients must satisfy these conditions: $(c_{TE})_{11} = 1$, $(c_{TE})_{12} = 0$; $(c_{TM})_{11} = 0$; $(c_{TM})_{12} = 1$. For these relations to hold, $\kappa_{TM}L = (2m_1-1)\pi/2$, $\kappa_{TE}L = m_2\pi$, with m_1 and m_2 positive integers. Thus, constraints on both coupling coefficients must be met simultaneously to satisfy the requirements for a PBS. Furthermore, from a practical standpoint it is desirable to make the coupler as short as possible, implying small values of m_1 and m_2. For $m_1 = m_2 = 1$, for example, $\kappa_{TM}L = \pi/2$ and $\kappa_{TE}L = \pi$, so $\kappa_{TE} = 2\kappa_{TM}$. This implies a considerably broader mode profile for the TE mode than for the TM mode, which is undesirable from the standpoint of mode matching to an optical fiber.

SHORT STATEMENT OF THE INVENTION

Accordingly, as opposed to those now known in the industry, the AOTF and EOTF apparatus and methods of the present invention do not require polarizing beam splitters. Further, because the invention provides an additional degree of freedom in achieving the required beam splitter performance, it is much easier to fabricate than prior art AOTFs and EOTFs which make use of polarizing beam splitters. In particular, a guided wave tunable filter of the present invention includes, in a preferred embodiment, two 3-port Y-branch beam splitters connected to form two spaced apart waveguides between said beam splitters, with an input port and an output port. The waveguides include an optical path difference of half a wavelength and polarization coupling regions in the two waveguides are displaced by half the spacial period of a pertubation responsible for coupling. Both acoustooptic and electrooptic tunable filters of the two port design

are disclosed. Additionally, in a preferred embodiment, a four port AOTF and a four port EOTF are also disclosed.

BRIEF DESCRIPTION OF THE DRAWINGS

Other objects, features and advantages of the present invention will become more fully apparent from the following detailed description of the preferred embodiment, the claims and the accompanying drawings in which:

FIGURE 1 is an illustration of a Prior Art AOTF;

FIGURE 2 is an illustration of a Prior Art EOTF;

FIGURE 3 is an illustration of a Prior Art four-port beam splitter;

FIGURE 4 is an illustration of a preferred embodiment of a four-port AOTF of the present invention;

FIGURE 5 is an illustration of a preferred embodiment of a four-port EOTF of the present invention;

FIGURE 6 is an illustration of a preferred embodiment of a two-port AOTF of the present invention; and

FIGURE 7 is an illustration of a preferred embodiment of a two-port EOTF of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The preferred embodiment of the present invention is illustrated by way of example in FIGURES 4-7. Filter designs introduced here for the purpose of relaxing constraints on beam

splitter characteristics are illustrated in Figs. 4 and 5. In general, these differ from the conventional designs of prior art Figs. 1 and 2 in the following respects: (1) polarizing beam splitters are not required, (2) the optical path difference for the waveguides between the beam splitters for both polarizations is a half-wavelength, or an odd integral multiple thereof, and (3) the relative positions of the polarization coupling regions in the two waveguides are displaced in the propagation direction by half the spatial period of the perturbation responsible for the coupling.

To analyze these new filter designs, the case of P polarization input with no polarization conversion is considered first. The transfer matrix for the filter is given by

$$\mathbf{O_P} = \mathbf{C_P M_\pi C_P I_P} \tag{7}$$

with $\mathbf{M}_\pi$ the matrix which describes the pi-radian relative phase shift due to the half-wavelength path difference, given by

$$\mathbf{M}_\pi = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \tag{8}$$

Evaluating the matrix product in eq. (7) yields

$$\mathbf{O_P} = \begin{bmatrix} (c_p)_{11}^2 - (c_p)_{12}^2 & 0 \\ 0 & (c_p)_{12}^2 - (c_p)_{11}^2 \end{bmatrix} \mathbf{I_P} \tag{9}$$

It follows from equations (5) and (6) that

$$O_P = M_\pi I_P \tag{10}$$

Since M_π is diagonal, all of the power incident in port i in either polarization exits from output port i. This represents the case of the non-selected frequencies for which no polarization conversion occurs in the waveguides. Power incident in port i couples part of the way to port j in the first coupler, but then couples back to port i in the second coupler.

For the case that polarization conversion occurs between incident polarization P and output polarization P', the transfer matrix is given by

$$O_{P'} = C_{P'} M_\pi M_\pi C_P I_P. \tag{11}$$

In this case, the light passes through the first coupler with polarization P and through the second coupler with polarization P'. The second factor M_π in eq. (11) accounts for the relative displacement of the coupling regions in the waveguides by half the spatial period of the pertubation responsible for the polarization coupling. Since M_π M_π equals the unitary matrix, eq. (11) immediately simplifies to

$$O_{P'} = C_{P'} C_P I_P . \tag{12}$$

From eqs. (4)- (6), and making use of the trigonometric relations cos (A+B) = cosAcosB - sinAsinB and sin(A+B)=sinAcosB + cosAsinB, it follows that

$$C_{P'} C_P = \begin{bmatrix} \cos(\Theta) & i\sin(\Theta) \\ i\sin(\Theta) & \cos(\Theta) \end{bmatrix} \tag{13}$$

with

$$\Theta = \kappa_{TE} L + \kappa_{TM} L . \tag{14}$$

where "TE" and "TM" have replaced "P" and "P'". The condition for complete power crossover to occur, such that all power incident in port i exits via output port j, is $\cos\Theta = 0$, or $\Theta = (2m_3 - 1)\pi/2$, with m_3 a positive integer. For the shortest couplers, with $m_3 = 1$, $\Theta = \pi/2$. It follows from eqs. (5), (6), and (14) that a condition for complete power crossover can be written

$$(f_{TE})_{ii} + (f_{TM})_{ii} = 1 \tag{15}$$

for i = 1 or 2, where $(f_P)_{ij}$ is the fraction of incident power with polarization P incident on the coupler in port j which exits via port i, given by

$$(f_P)_{ij} = |c_P|_{ij}^2 \tag{16}$$

ALTERNATIVES

As illustrated in Figs. 4 and 5, the disclosed filters of the present invention perform the "drop" function of removing one optical wavelength or frequency and allowing all others to propagate. These same filters can perform the "add" function, as illustrated by the same Figs. 4 and 5 with the direction of the light propagation (as indicated by arrows in the diagrams) reversed.

Tuning of the apparatus shown in Figs. 4 and 5 enables the achievement of optimum performance in various circumstances. In every circumstance, it is required that the optical path difference in the MZI equal an odd integral multiple of a half wavelength, which is satisfied by a physical path difference of 350 nm in $LiNbO_3$ at 1.53 μm wavelength for extraordinary polarization. For this path difference, a phase error of about 0.1 rad results for the ordinary polarization due to the large substrate birefringence. This error is readily compensated by a section of waveguide outside the polarization conversion region in which the birefringence is altered by either a strain-inducing film or an electrooptic interaction.

It should also be noted that, in the case of the AOTF, the relative displacement of the polarization coupling regions in the two waveguides as a fraction of the polarization beat length in the waveguides changes with tuning of acoustic frequency. The effect is significant, amounting to about $\pm$ 0.15 rad for tuning of the optical frequency by $\pm$ 1 THz, but is correctable through the use of a phased array or tilted finger chirped acoustic transducer design in which the propagation direction of the acoustic wave changes in angle linearly with acoustic frequency

The condition given in eq. (15), which must be satisfied by couplers for the new filter designs of the present invention, can readily be achieved in practice. For example, in a preferred embodiment, the effective coupling length L and the waveguide width are fixed a priori, with coupling strengths κ_p for the two polarizations determined by an appropriate choice of waveguide separation. The κ_p values are both monotonically decreasing functions of waveguide separation. By measuring $(f_{TE})_{ii}$ and $(f_{TM})_{ii}$ for test coupler patterns with different waveguide separations, a separation for which eq. (15) is satisfied can readily be determined.

Since the filters of the present invention will be used in fiber optic systems, it is desirable to match the mode electric field patterns for both polarizations as closely as possible to a single mode fiber field pattern. This is a consideration in determining the waveguide fabrication procedure. For example, if the waveguides are formed by Ti diffusion in $LiNbO_3$, the diffusion time and temperature should be chosen with this in mind. Even so, it is expected that there would be significant differences in the TE and TM mode profiles, which would be reflected in the coupling constant values κ_{TE} and κ_{TM}. These differences, however, do not pose a problem in implementing the new filter designs of the present invention.

By contrast, two constraints must be satisfied simultaneously for the PBSs used in conventional tunable filter designs, making it much more difficult to achieve the needed coupler performance. Thus, the invention considers a PBS optimization procedure in which the waveguide width and coupling length are fixed and the waveguide separation is varied. A waveguide separation for which complete crossover is achieved for TE polarization would not, in general, also meet the companion requirement of providing complete straight through propagation for the TM polarization.

In practice, considerable prior art effort has been devoted to solving the PBS problem for tunable filters by using two mode interference and Ti-indiffused/proton exchanged waveguide combinations. Although polarization extinction ratios > 20 dB have been reported, the techniques to achieve them are complicated and reproducibility has been a major problem. Due to difficulties with the integrated PBSs, some AOTF demonstrations have utilized bulk PBSs external to the $LiNbO_3$ substrate in which the acoustooptic interaction takes place.

Simpler 2-port filters of the present invention, designed using the same principles as the 4-port devices, are illustrated in Figs. 6 and 7. These 2-port filters are designed to transmit a selected wavelength channel and block all others. In the 2-port filters, two 3-port Y-branches replace the two 4-port beam splitters employed in the designs of Figs. 4 and 5. If the 3-port branches are symmetric, the splitting ratios will be 50% for both polarizations and the condition of eq. (15) is automatically satisfied. As with the 4-port filters of the present invention, the optical path difference for the waveguides between the beam splitters for both polarizations is a half-wavelength, or odd integral multiples thereof, and the relative positions of the polarization coupling regions in the two waveguides are displaced in the propagation direction by half the spatial period of the pertubation responsible for the coupling.